Dynamical Evolution of a Circumbinary Disk and its Effect on the growth and Sedimentation of Dust Particles

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Introduction

A planet-forming nebula is a dynamic environment whose properties and structure vary with time. The dynamics of such an environment, and its time-varying structure have considerable effects on the dynamics and formation of small solids. Among such structures, regions where the pressure of the gas is locally enhanced are of particular interest. The appearance of such regions along with the combined effects of gas-drag and pressure gradients causes solid particles in their vicinities to migrate toward their centers, and accumulate in that region. While migrating, solid particles sweep up smaller objects and grow in size. In this paper, the effects of the appearance of pressure-enhanced structures on the growth and accumulation of micron-sized particles are studied, and the effects of gas-drag and pressure gradients on the rate of accumulation of centimeter-sized objects in the regions of local maximum pressure on the midplane are discussed.

Gas Drag and Pressure Gradients

The combined effect of gas drag and pressure gradients causes solid particles in the vicinity of pressure-enhanced regions to migrate toward the center of these locations. A positive pressure gradient increases the effective central acceleration and causes the gas to rotate more rapidly. This results in rapid rotation of the particles in the gas, hence, their outward migration. The opposite is true for a negative pressure gradient (Fig. 1). In hydrostatic equilibrium, pressure gradients causes the nebula to rotate with a velocity slightly different from Keplerian. That is,

$$r\omega_g^2 = r\omega_K^2 + \frac{1}{\rho_g}\frac{dP_g}{dr} \qquad , \quad \omega_K^2 = \frac{GM}{r^3}$$

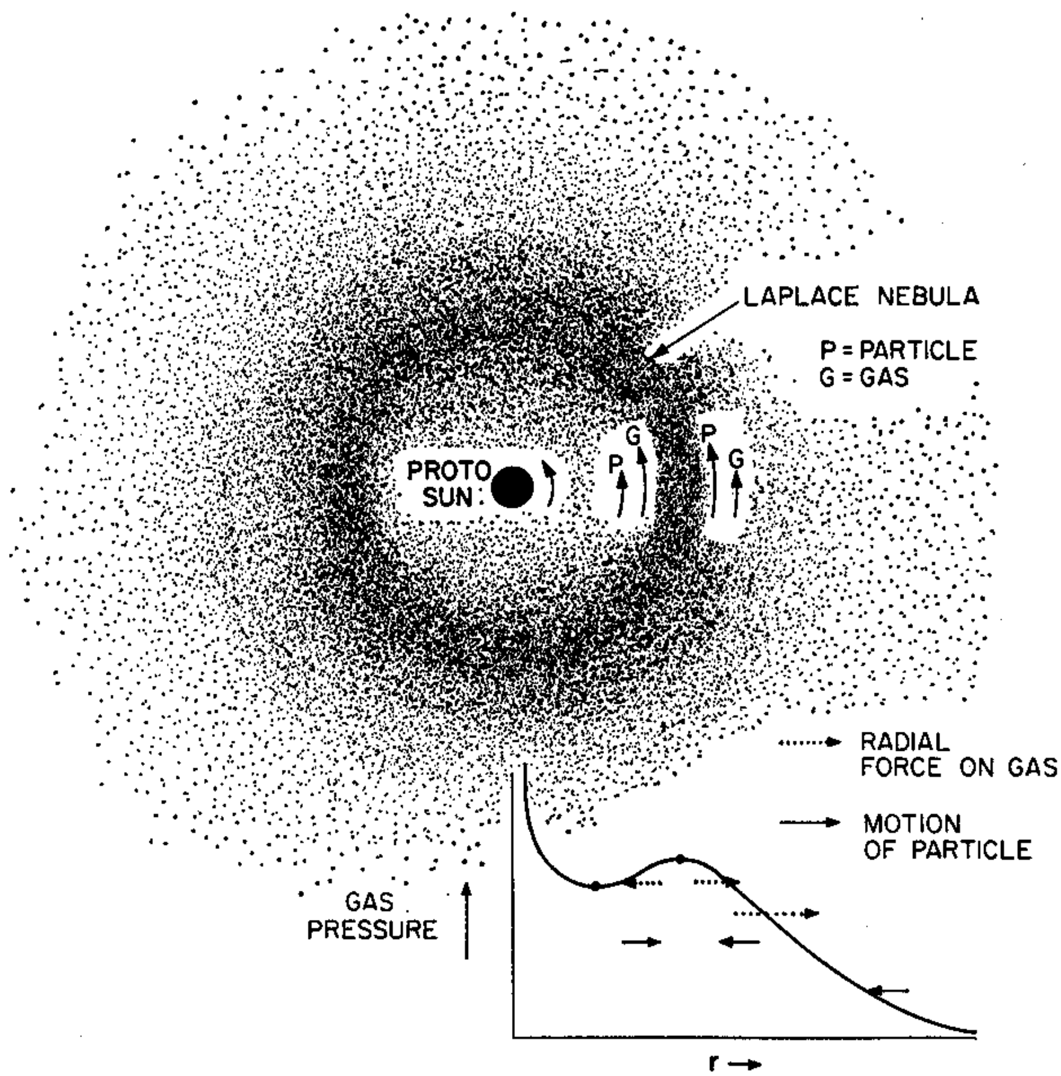

Figure 1

Gas Drag

A solid object in the gas is subject to the drag force of the gas. Depending on its size, R_d, gas drag may be in the Epstein, or Stokes regimes.

- Epstein Drag ($R_d << \lambda, |\vec{V}_{rel}| = |\vec{V}_g - \vec{V}_d| << \bar{V}_{th}$)

$$\vec{F}_{D,E} \;=\; \frac{4\pi}{3}\, R_d^2\, \rho_g\, V_{th}\, \vec{V}_{rel}$$

- Stokes Drag

$$\vec{F}_{D,S} \;=\; \frac{1}{2}\, \pi\, C_D\, R_d^2\, \rho_g\, V_{rel}\, \vec{V}_{rel}$$

In these equations, the subscript d represents the particle, and g represents the gas. The quantity V_{th} in Epstein drag is the thermal velocity of the gas molecules, and λ represents their mean free path. The coefficient C_D in the Stokes drag is the drag coefficient. For the particles of interest in this study, C_D=24/Re, where Re is the gas Reynolds number. The formula for the drag force used in this study is given by

$$\vec{F}_D \;=\; (1 \,-\, \mathcal{F})\, \vec{F}_{D,E} \,+\, \mathcal{F}\, \vec{F}_{D,S}$$

where $\mathcal{F} \;=\; R_d/(R_d \,+\, \lambda)$. This formula assures that at any time during the growth of an object, a correct contribution of both Epstein and Stokes drag forces are included in its dynamical equations.

A Heuristic Model

To focus attention on the growth of dust grains in the vicinity of pressure-enhanced regions, and the effects of changes in the gas density and temperature on the rate of particle growth, an isothermal and turbulence-free nebula is considered here with a gas density given by

$$\rho_g(r,z) \;=\; \rho_g(r,0)\,\mathrm{Exp}\left\{\frac{8GM}{\pi V_{th}^2}\left[\frac{1}{(r^2+z^2)^{1/2}}-\frac{1}{r}\right]\right\}.$$

In this equation, G and M are the gravitational constant, and the mass of the central star, and

$$\rho_g(r,0) \;=\; \rho_0\,\mathrm{Exp}\left[-\beta\left(\frac{r}{r_m}-1\right)^2\right]$$

is the gas density function on the midplane of the nebula. The quantities ρ_0, β and r_m have constant values, which in this study have been chosen to be

- $\rho_0 = 10^{-10}$ g/cm^3

- $\beta = 1$

- $r_{\mathrm{m}} = 1$ AU.

The temperature of the gas is 300 K. Figure 2 shows the density function of this model nebula at different location. As shown here, the nebula has regions of density(pressure) enhancement on any plane parallel to the midplane. A particle in this nebula migrates toward the location of density enhancement while descending toward the midplane. This causes particles to accumulate around the maximum density structure of the midplane.

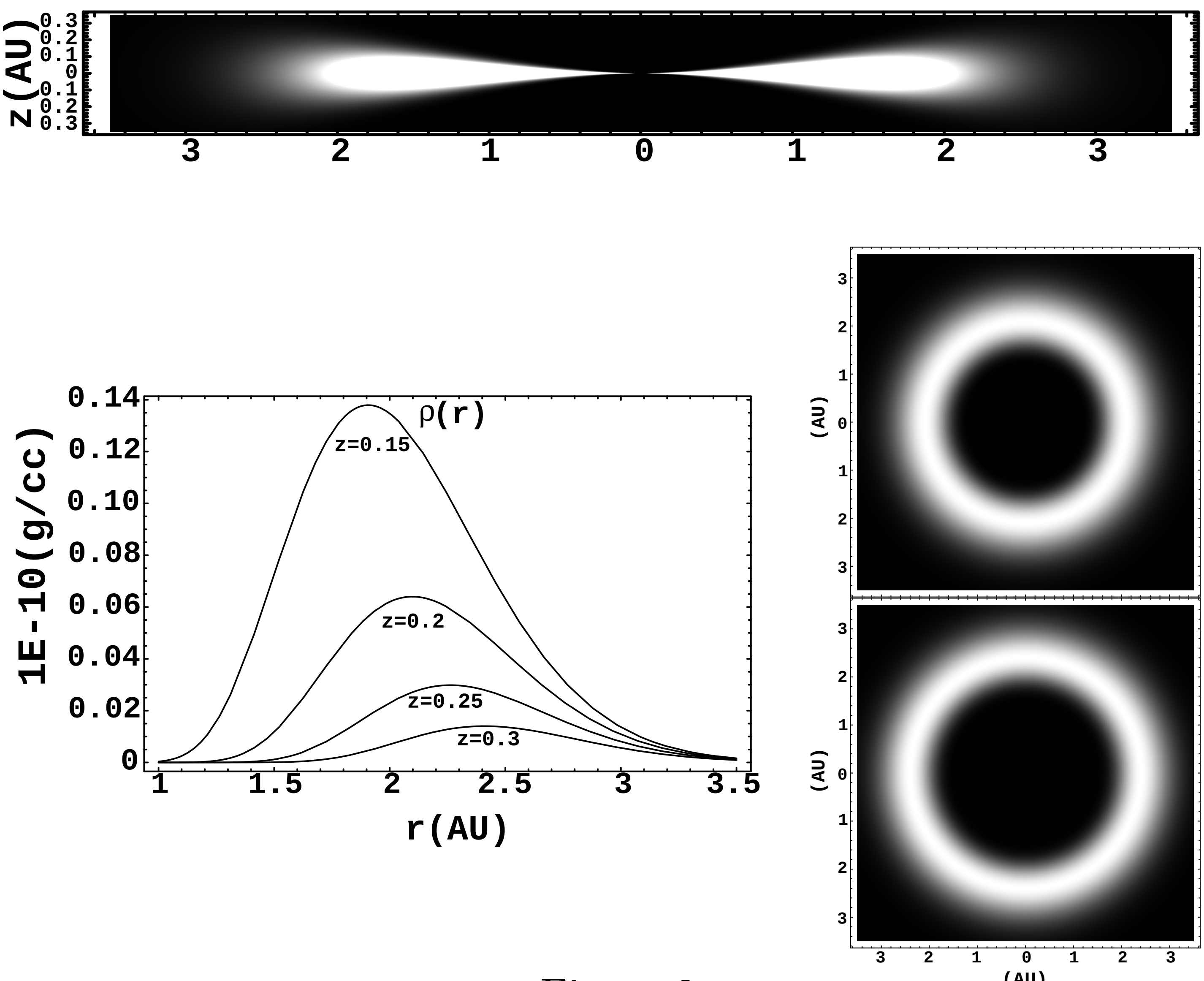

Figure 2

Pressure Gradients Induced Migration

Solid objects undergo radial migration toward the location of the maximum gas density while descending toward the midplane. Figure 3 shows the radial and vertical motions of small grains in the model nebula considered here. As expected, micron-sized objects are strongly coupled to the gas and take a long time to undergo substantial migration.

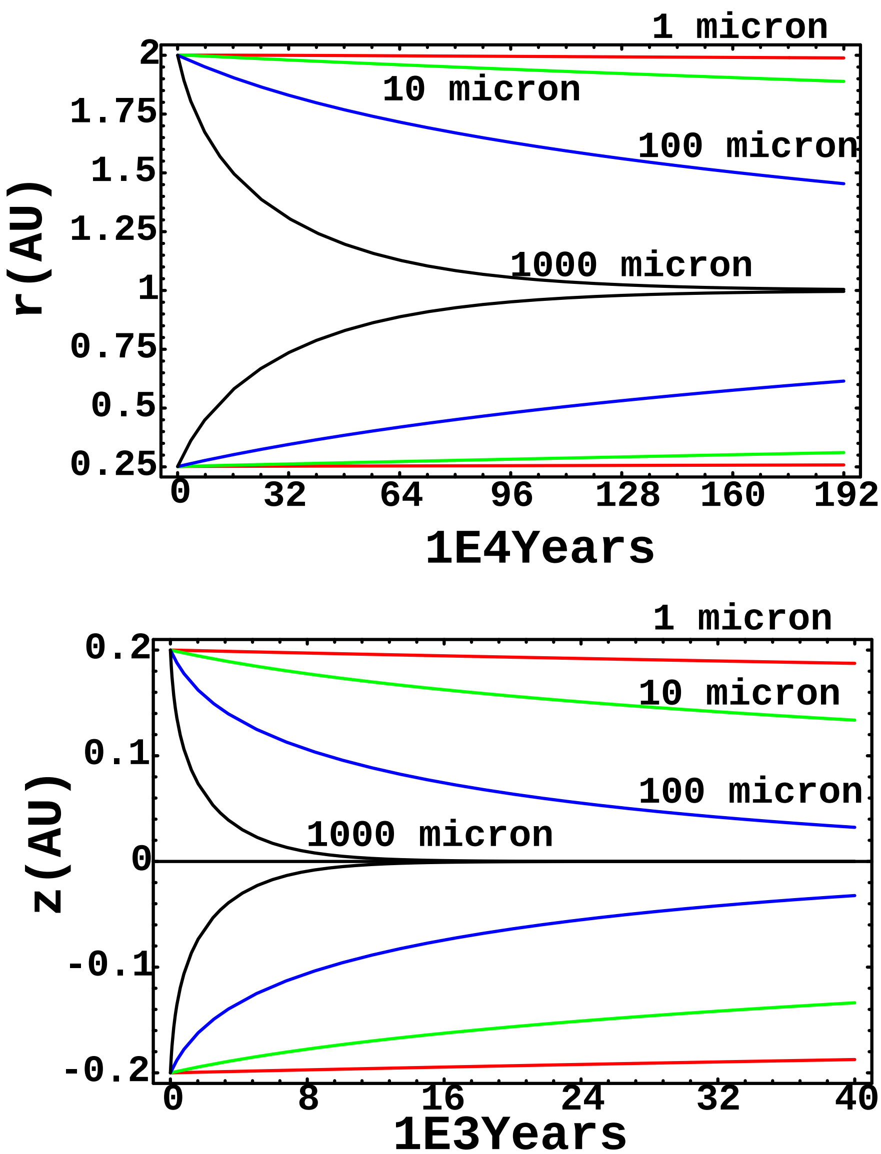

Figure 3

Solids Growth

The particles of interest in this study range between 1 to 1000 micron in size. It is assumed that the nebula is a mixture of molecular hydrogen and 0.1 micron solid particles with a distribution proportional to the gas density function. That is,

$$\text{Solids spatial density} = f \ (\text{Gas density})$$

The possibility of collision and coalescence of two solid objects is proportional to their relative velocity. That means, assuming a perfectly inelastic collision between two objects, their rate of mass-growth will be proportional to their mutual relative velocity. In this study, it is assumed that a solid object sweeps up all smaller background grains on its way. Because the particles of the background are strongly coupled to the gas, when studying the growth of an object, it is assumed that the rate of its mass-growth is proportional to its velocity relative to the gas. Figure 4 shows the growth, and the radial and vertical migration of a 10 micron-sized grain with a solid/gas of $f = 0.0034$. For a comparison, the migrations of the object without mass-growth ($f = 0$) have also been shown. As shown here, while the object sweeps up the particles of the background, the rates of its vertical and radial motions increase. This results in rapid accumulation of cm-sized particles around the midplane of the nebula.

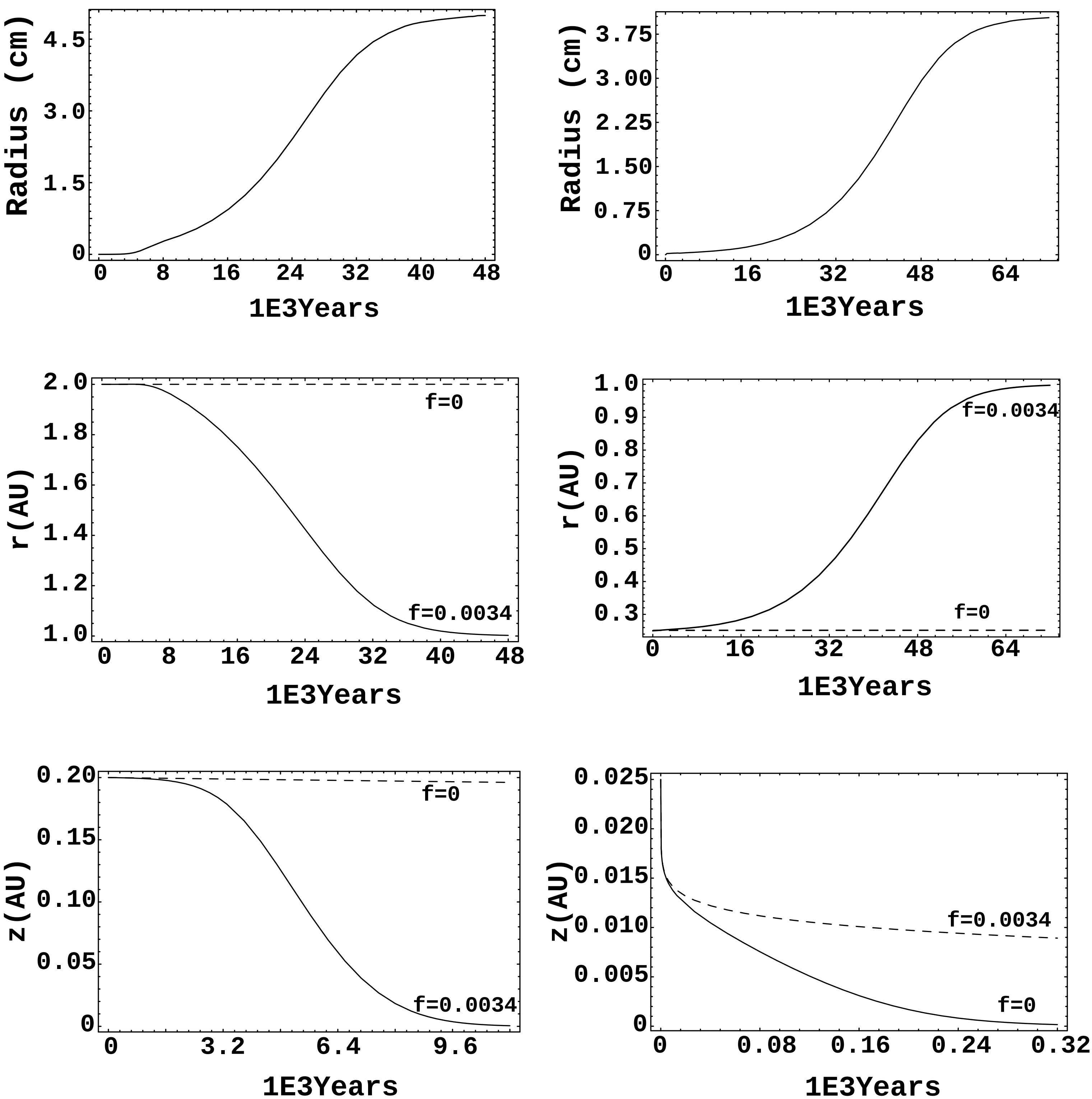
Radius (cm)
4.5
3.0
1.5
0
0
8
16
24
32
40
48
1E3Years
Radius (cm)
3.75
3.00
2.25
1.50
0.75
0
0
16
32
48
64
1E3Years
r(AU)
2.0
1.8
1.6
1.4
1.2
1.0
f=0
f=0.0034
0
8
16
24
32
40
48
1E3Years
r(AU)
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
f=0.0034
f=0
0
16
32
48
64
1E3Years
z(AU)
0.20
0.15
0.10
0.05
0
f=0
f=0.0034
0
3.2
6.4
9.6
1E3Years
z(AU)
0.025
0.020
0.015
0.010
0.005
0
f=0.0034
f=0
0
0.08
0.16
0.24
0.32
1E3Years

Figure 4

Conclusion

A planet-forming nebula is a dynamic environment. During the formation of solid bodies, particularly at the stage when micron-sized particles collide to form larger objects, it is necessary to monitor this environment at all times. When the density or pressure of the gas maximizes locally, micron-sized objects in its vicinity undergo faster approach toward the midplane while sweeping up the particles of the background. This causes rapid accumulation of centimeter-sized bodies in that region and results in the formation of a turbulent layer near the midplane. The shear-induced turbulence increases the rate of collision of cm-sized bodies and enhances the rates of their growth to meter-sized and larger objects.

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